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SOIL DISINFECTION WITH HOT WATER TO CONTROL THE ROOT-KNOT NEMATODE AND PARASITIC SOIL FUNGI.

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OBJECTS OF THE INVESTIGATIONS.

The experiments described in the following pages were undertaken to obtain more accurate data on the effectiveness of hot water as a means of ridding soil of the root-knot nematode (*Heterodera radicicola*) (Greef.) Müller) and parasitic fungi usually associated with damping-off and other root troubles.

The great need of a simple, practical method for disinfecting small quantities of soil in which to grow healthy seedlings for home-garden planting has always existed, but because of the great extension of tomato and other club work in recent years, the need has become more pronounced and more apparent. Such a method would also be especially adapted for disinfecting soil in pots and shallow greenhouse benches. Very successful results have been obtained by one of the writers in killing the root-knot nematode in infested dasheen tubers, to be used for planting purposes, by soaking them in hot water, without appreciably impairing their viability. Furthermore, a method of soil disinfection by hot water has been used with some success in vegetable greenhouses in the Boston district, but no careful experiments have been carried out to determine the temperatures required or the quantity of water necessary to control the soil troubles

successfully. It is not thought that the hot-water method will take the place of steam for soil-disinfecting purposes where steam can be advantageously used. On the other hand, it is intended for use where steam is not available or where its use is for any reason impracticable. Many greenhouses are so constructed that the use of inverted pans for steaming the soil is not feasible. In some greenhouses the capacity of the boilers is not sufficient to furnish the high pressure steam required for disinfecting purposes. For disinfecting small quantities of soil in pots or flats, to be used in growing seedling plants for home gardens or in greenhouses, steam is rarely available, and its use is often impracticable.

So far as the writers have been able to ascertain, the only investigations that have been carried out with hot water for soil disinfection are those of Stone and Smith in "The Rotting of Greenhouse Lettuce," Bulletin 69 of the Massachusetts (Hatch) Agricultural Experiment Station, published in 1900. Working with deep ground beds of greenhouse soil, they found that by the liberal application of water at 210° F. as it came from the hose the temperature of the upper 4 inches of soil was raised to 176° to 186° F. The treatment completely killed the Rhizoctonia and reduced the amount of lettuce drop caused by *Sclerotinia libertiana* 76 per cent.

In carrying out the investigations here reported, two series of experiments were performed, the second being in a large measure a repetition of the first, but with certain changes and additions suggested as a result of the first tests.

EXPERIMENT SERIES I.

METHOD OF PROCEDURE.

SOIL.

The soil used in the experiments was a light, loose, sandy mixture made of about one-third standard greenhouse soil and two-thirds sand. Such a mixture is very favorable for the growth of nematodes. For some time previous to the initiation of the experiments, the soil had been in a bench section in the greenhouse which had been used for growing tomatoes for maintaining a large stock culture of nematodes. It was, therefore, well infested with the root-knot nematode and with damping-off fungi, as was shown by previous results on tomatoes grown therein as well by the subsequent observations with untreated checks. To insure uniform physical condition and uniform distribution of the pathogenes throughout the entire mass of soil, it was thoroughly mixed by shoveling over several times, and was then sifted through a coarse screen. To obtain more abundant infection, in in some cases, as noted in detail below, tomato roots severely diseased with root-knot were cut up into small pieces and mixed with the soil.

TREATMENT OF THE SOIL.

The soil was then placed in standard 4 and 8 inch unglazed earthen pots and in a section of a raised greenhouse bench. Inasmuch as the soil in different containers received different treatments, each series of experiments is here considered separately.

Four-inch pots.—The 4-inch pots were treated by immersing them for 2½, 5, and 10 minutes, respectively, in boiling water at 98° C. (208° F.). Three pots were included in each treatment, and one was left untreated as a check. The soil used was taken from the greenhouse bench described, but was not further infected by the addition of nematode-infested roots. During the immersion of the pots the water was kept boiling by means of two large Bunsen burners. The check pot was immersed for a short time in cold water. Following the immersion, the pots were removed and the surplus water allowed to drain off. They were then placed on the greenhouse bench, which was covered with a layer of fresh cinders, to reduce the possibility of reinfestation with nematodes, and allowed to dry for five days before planting.

This experiment was duplicated, using the same sifted soil plus nematode galls of tomato roots. These galls were cut up into small pieces, about one-third inch long, and mixed with the soil in the top half of the pots.

Eight-inch pots.—The 8-inch pots were filled with the infested soil to within 1 to 1½ inches of the top when well shaken down. Three pots each were then treated by applying 1,000, 2,000, and 3,000 c. c., respectively, of boiling water at 98° C. (208° F.). An additional pot was thoroughly wet down with cold water and left as a check. In the case of the 1,000 c. c. treatment, the boiling water was all applied at one time, but with the larger treatments it was added as rapidly as it penetrated the soil.

As soon as the respective quantities of water were added, the pots were covered with newspapers to hold in the heat, and the surplus water was allowed to drain off. The pots were then left on the greenhouse bench to dry for five days previous to planting.

This experiment was also duplicated, using sifted infested soil plus nematode-infested tomato roots cut up and thoroughly mixed with the topsoil in the pots.

Greenhouse bench.—A portion of a greenhouse bench about 3 by 4 feet was divided into four sections approximately 18 by 26 inches by means of 1-inch boards which extended to the bottom of the bench and about 2 inches above the surface of the soil, which was about 5 inches deep. The soil was the same as that used for the pot experiments described above, except that it was not sifted and did not receive additional nematode-infested tomato roots.

Section 4 received an application of approximately 17,000 c. c. (17 liters) of cold water and acted as a check. To sections 1, 2, and 3 were applied, respectively, 8,500, 13,500, and 17,000 c. c. of boiling water, which is approximately equivalent to an application of 750, 1,000, and 1,500 c. c. per 8-inch pot of soil. In the case of section 1 the whole quantity was applied at one time; on sections 2 and 3 the hot water was applied in two doses put on a few minutes apart, for the reasons that the soil would not take up the entire volume of water at one time, and, furthermore, the means for heating this quantity at once were not at hand. In the case of section 1 the water applied was sufficient to wet thoroughly all the soil, and a small proportion ran through. In sections 2 and 3 a considerable proportion of water ran through, but it was noted that the first dose compacted the soil to a certain extent, so that the second dose ran through but slowly. To further assist in holding the heat in the soil, the sections were covered with newspapers immediately following the treatment. The bench sections were left for seven days, to allow the soil to dry out sufficiently for planting.

PLANTING OF SEED.

In the 4 and 8 inch pot experiments, Stone tomato seeds were sown five days after the treatment, fairly thick, but as uniformly as possible. In the bench sections two rows each of Stone tomatoes and Big Boston lettuce were sown in a similar manner, especial care being taken to make the sowings as uniform as possible in the different sections.

RESULTS.

The results from these experiments were recorded in the form of comparative germination counts taken two weeks after planting, and notes made at intervals on the damping-off and nematode infection and on the size and vigor of the plants. All the plants were allowed to grow for about seven weeks, and the experiment was then terminated. All the plants were removed from the pots and benches, and the soil was washed carefully from the roots, especial care being taken to preserve the entire root systems intact. The plants were then examined for nematode galls or injuries due to the attacks of soil fungi, records being made of the number and severity of each. Isolations were made to determine the organism responsible for the damping-off and root discolorations found. *Pythium debaryanum* was found to be the cause of damping-off, while Rhizoctonia species caused stem lesions and root discolorations. All data obtained were supported by photographs taken at various stages during the progress of the experiment to illustrate the important results noted. The details of the results are given in Tables I and II.

TABLE I.—*Soil-disinfection tests with tomato plants grown in 4-inch and 8-inch pots, with hot-water treatment, in February and March, 1918.*

[All the pots were filled with nematode-infested soil thoroughly mixed by sifting, soil *A* being without the addition of diseased tomato roots and soil *B* having such addition.]

Size of pots, kind of soil used, and treatment of soil-filled pots.	Pot. No.	Number of living plants.		Results observed on Mar. 7 (end of experiment).[1]								
				Nematode infestation of roots.							Plant notes.	
								Percentage.				
		On Feb. 5.[2]	On Mar. 7.	Severe.	Medium.	Mild.	Total.	By pot.	By treatment.	Pythium and Rhizoctonia infection of roots.	Height (inches).	Color.
Four-inch pots, soil *A*: Immersed in boiling water—												
2½ minutes	1	32	31	0	0	0	0	0	0	Wh	5 to 6.	Hg.
	2	40	43	0	0	0	0	0				
	3	37	39	0	0	0	0	0				
5 minutes	1	43	44	0	0	0	0	0	0	Wh	5 to 7.	Hg.
	2	37	37	0	0	0	0	0				
	3	36	36	0	0	0	0	0				
10 minutes	1	78	75	0	0	0	0	0	0	Wh	..do..	Hg.
	2	30	29	0	0	0	0	0				
	3	37	39	0	0	0	0	0				
Check (immersed in cold water)	1	7	6	0	2	2	4	66	83	Db	3.....	Sg.
	2	17	6	3	3	0	6	100				
Four-inch pots, soil *B*: Immersed in boiling water—												
2½ minutes	1	88	58	0	0	0	0	0	0	Md. Wh Wh	5 to 6.	Hg.
	2	25	26	0	0	0	0	0				
	3	33	34	0	0	0	0	0				
5 minutes	1	64	65	0	0	0	0	0	0	Wh	5 to 7.	Hg.
	2	40	45	0	0	0	0	0				
	3	45	52	0	0	0	0	0				
10 minutes	1	33	47	0	0	0	0	0	0	Wh	..do...	Hg.
	2	22	20	0	0	0	0	0				
	3	42	42	0	0	0	0	0				
Eight-inch pots, soil *A*: Boiling water poured into pots—												
1,000 c. c.	1	52	31	0	0	14	14	45	20.5	Nad	3 to 4.	Yg.
	2	82	83	0	0	21	21	25				
	3	69	66	0	0	2	2	3				
2,000 c. c.	1	70	73	0	0	6	6	8	8.8	Nd Sd. Wh	4 to 5.	Dhg.
	2	104	101	0	2	11	13	13				
	3	76	75	0	0	3	3	4				
3,000 c. c.	1	121	126	0	0	0	0	0	0	Wh	..do..	Dhg.
	2	86	88	0	0	0	0	0				
	3	87	86	0	0	0	0	0				
Check (drenched with cold water)	1	34	13	15	2	3	10	77	83	Db	2.....	Sg.
	2	11	5	13	1	1	5	100				
Eight-inch pots, soil *B*: Boiling water poured into pots—												
1,000 c. c.	1	66	65	0	0	16	16	24	19.6	Nad	3 to 4.	Yg.
	2	76	71	0	0	13	13	18				
	3	84	76	0	4	8	12	16				
2,000 c. c.	1	85	76	0	0	17	17	22	16.7	Sd.	4 to 5.	Dhg.
	2	52	52	0	0	4	4	8				
	3	81	80	0	0	14	14	17				
3,000 c. c.	1	55	56	0	0	0	0	0	0	Wh	..do..	Dhg.
	2	66	96	0	0	0	0	0				
	3	52	46	0	0	0	0	0				

[1] Abbreviations used: Db=Discolored, badly diseased; Dhg=Dark, healthy green; Hg=Healthy green; Md=Many discolored; Nad=Nearly all discolored; Sd=Slight discoloration; Sg=Sickly green; Wh=White, healthy; Yg=Yellow green.

[2] Two weeks after planting.

DISCUSSION OF RESULTS.

From a study of the data presented in Table I, relative to the two sets of 4-inch pot treatments, the results are here summarized.

1. As a result of submersion of the soil in boiling water for 2½, 5, and 10 minutes, no infection by root-knot nematodes, Pythium, or Rhizoctonia occurred in either set of pots except in one pot which showed a small amount of Rhizoctonia root discoloration. As this minor infection occurred in one of the pots to which diseased roots were added and which received the 2½-minute submersion, it is quite probable this was due to insufficient treatment. The plants in the check pots showed 83 per cent affected by nematodes and 100 per cent severely diseased by the fungous parasites. A comparison of the typical appearance of roots from treated pots and those from untreated check pots is shown in Plate I, figure 1.

2. Normal germination occurred in all treated pots, an average of 42 plants per pot, while in the untreated pots the stand was reduced by the soil organisms to an average of 12 plants per pot.

3. All treatments prevented damping-off in both sets of pots, as was shown by the final examination, while in the untreated check pots half of the seedlings died after the first germination count made two weeks subsequent to planting. (Pl. I, fig. 2.)

4. Throughout the experiment the plants in the check pots showed pronounced yellowing and stunting, reaching an average height of only 3 inches at the time of the final examination, as compared to an average height of 5 to 7 inches for the plants in treated soil, all of which were vigorous and of a healthy green color.

Certain facts evident from a study of that part of the data in Table I pertaining to the two sets of 8-inch pot experiments are here presented.

1. The 18 treated pots showed an average of 74 seedlings per pot two weeks after planting, as compared with an average of 22 for the two check pots, a reduction of 70 per cent in the stand. The typical appearance of treated and untreated pots at this time is shown in Plate II, figure 1.

2. A slight amount of damping-off occurred in two of the six pots receiving the 1,000 c. c. treatment, while none was noted in the 12 pots which received the larger amounts of boiling water. In the check pots, however, almost 60 per cent of the seedlings damped-off between the first germination count and the final notes.

3. The plants in the check pots remained markedly stunted throughout the experiment, attaining a final average height of only 2 inches, and were considerably yellowed and unhealthy in appearance. The plants grown in pots receiving 1,000 c. c. of boiling water reached a final height of 3 to 4 inches and were slightly yellow in color. The plants in all pots receiving the larger treatments grew

to 4 to 5 inches in height, and all were vigorous and healthy in appearance. Differences existing at the end of the experiment in number, size, and general appearance of the plants in pots receiving the different treatments are shown in Plate II, figure 2. Compare with Plate II, figure 1, which shows some of the same pots at a very early stage in the experiment.

4. The application of 3,000 c. c. of boiling water per 8-inch pot (180 cubic inches of soil) gave complete control of both nematodes and soil fungi in both sets of pots. Applications of 1,000 c. c. and 2,000 c. c. gave partial control of the pathogenes. An average of 20 and 13 per cent, respectively, of the plants in these pots showed mild nematode infection, as compared with 83 per cent of nematode infection in the check pots, most of which was severe. In two of the six pots receiving the 2,000 c. c. treatment no Rhizoctonia infection occurred, while plants in the remaining pots showed slight root discolorations. Nearly all plants, however, which received the 1,000 c. c. treatment showed root discolorations. The roots of the plants in the untreated check pots were badly discolored, many being entirely destroyed by the fungous parasites. A comparison of the appearance of the roots from plants grown in treated and untreated soil is shown in Plate III.

TABLE II.—*Soil-disinfection tests with tomato and lettuce plants grown in shallow bench sections, with hot-water treatment, in February and March, 1918.*

[The bench sections were 5 to 6 inches deep and filled with nematode and fungus-infested soil thoroughly mixed by sifting.]

Kind of plants and bench section No.	Size of bench sections.	Application of boiling water (at 98° C.).			Damping-off on Feb. 5.	Results observed on Mar. 8, 1918 (end of experiment).									
		Total quantity.	Number of doses.	At rate per 8-inch pot.		Total plants.	Nematode infestation of roots.					Pythium and Rhizoctonia infection of roots.		Plant notes.	
							Severe.	Medium.	Mild.	Total.	Percentage.	Number of plants.	Percentage.	Height.	Color.[1]
Tomato:	*Inches.*	*C. c.*		*C. c.*	*No.*									*In.*	
1	26 by 18	8,500	1	750	3	108	0	0	43	43	40	66	61	6	Hg.
2	26 by 16	13,500	2	1,000	0	94	0	0	28	28	30	0	0	6	Hg.
3	24 by 18	17,000	2	1,500	0	204	0	4	10	14	7	3	14	7	Hg.
4 check[2]	24 by 16				15	75	15	21	18	54	72	75	100	4	Sy.[3]
Lettuce:															
1	26 by 18	8,500	1	750	65	178	0	28	43	71	40	178	100	2½	Y.
2	26 by 16	13,500	2	1,000	5	197	0	0	21	21	11	32	16	3	Hg.
3	24 by 18	17,000	2	1,500	0	210	0	0	2	2	1	0	0	5	Hg.
4 check[2]	24 by 16				25	32	6	12	2	20	64	32	100	2	Sg.[4]

[1] Abbreviations used: Hg=Healthy green, Sg=Sickly green, Sy=Stunted yellow.
[2] Saturated with cold water. [3] Poor stand. [4] Stand 25 per cent.

From the details of the bench experiments, which are given in Table II, the results are here briefly stated.

1. Damping-off of both lettuce and tomato seedlings on February 5 was quite prevalent in the check and in the section receiving 8,500 c. c. of boiling water, while it was found only to a slight extent in the 13,500 c. c. treated section and not at all in the 17,000 c. c. treatment.

2. The average percentages of netamode infection occurring on lettuce and tomato plants grown in treated sections Nos. 1 to 3 and check section No. 4 were as follows: 40, 20, 4, and 68. For Rhizoctonia they were 80, 8, 7, and 100. These figures indicate control of the pathogenes in proportion to the amount of the hot-water applications. A comparison of healthy plants from the 17,000 c. c. section with typical nematode and Rhizoctonia diseased plants, from the check section is shown in Plate IV, figure 1.

3. In the case of both test crops, while the plants in the untreated section, No. 4, were dwarfed and yellowed, in the treated sections they were of larger size and greater vigor the larger the amount of hot water applied. The stand in the check sections was greatly reduced. These points are clearly brought out in Plate III, figure 2.

EXPERIMENT SERIES II.

In studying the results secured from the preliminary experiments already presented, additional data were desired to answer certain questions which arose, viz: How much of the vigor and increased growth of the plants in treated soil was due to the physical and chemical effects of the heating on the soil, and how much to the absence of plant pathogenes? What temperatures were secured in the soil by the various treatments given and for what lengths of time were they maintained?

To answer these questions and also to make our results the more conclusive, on May 3 the entire series of experiments was repeated with more checks and with such changes and additions as would give the desired information.

METHOD OF PROCEDURE.

SOIL.

Two lots of soil were used in the 4 and 8 inch pot experiments, viz, infested soil and presumably uninfested greenhouse soil. The infested soil used was the nematode and fungus infested soil from the previous bench experiment with the addition of infested soil from the tomato bed used as a stock culture for nematodes. This was thoroughly mixed and sifted and was further infected with nematodes by mixing with the soil in the pots badly nematode-diseased tomato roots cut into small pieces. The greenhouse soil was from a fresh mixture not yet used in greenhouse work and presumably free from the parasites under consideration.

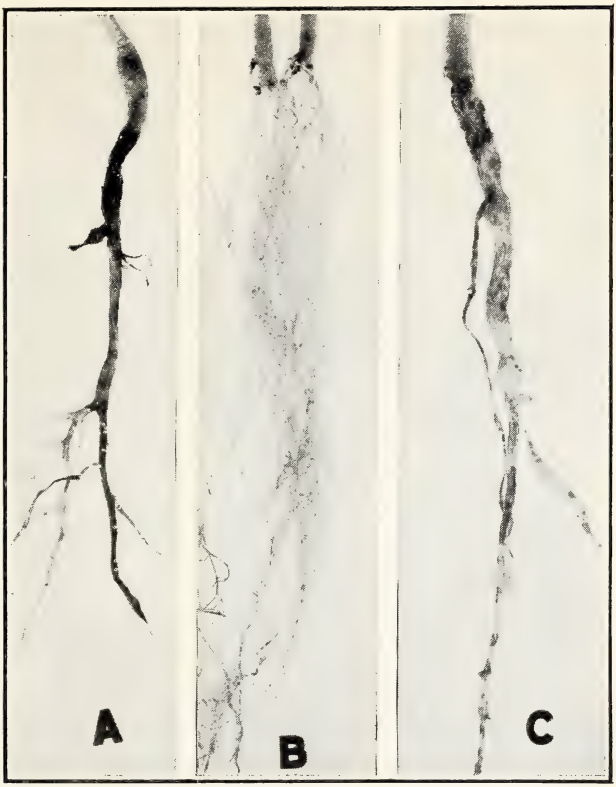

FIG. 1.—TOMATO PLANTS FROM TREATED AND UNTREATED 4-INCH POTS OF EXPERIMENT SERIES I.

B, Uninfected healthy roots grown in nematode and fungous infested soil submerged for 2½ minutes in boiling water (98° C.) (natural size); *A* and *C*, plants with nematode root and stem galls and Rhizoctonia root discolorations grown in untreated infested soil in check pots. (Enlarged three times.)

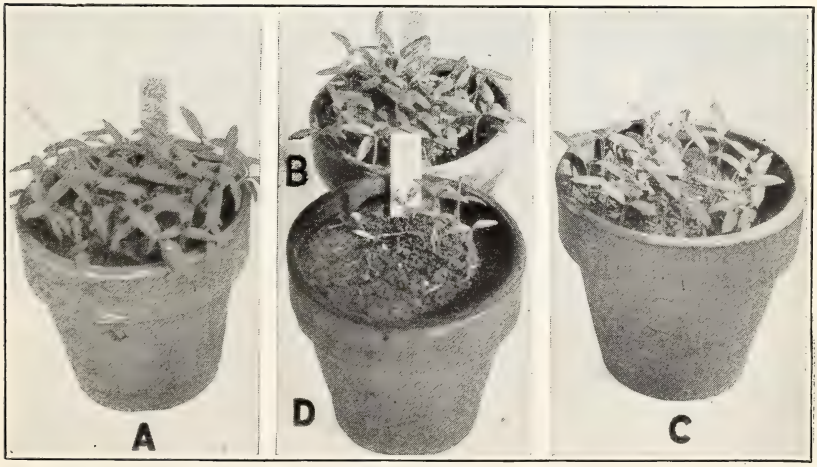

FIG. 2.—FOUR-INCH POTS OF EXPERIMENT SERIES I TWO WEEKS AFTER PLANTING.

Note the full stand and vigorous appearance of the tomato seedlings in pots *A*, *B*, and *C* submerged for 2½, 5, and 10 minutes, respectively, in boiling water, compared with the very poor stand, smaller size, and damping-off of plants in the untreated check pot *D*.

FIG. 1.—Note the full stand and vigorous appearance of the seedlings in pots *A* and *B*, which received the 3,000 and 1,000 c. c. treatments, respectively, as compared with the very poor stand and small size of seedlings in the check pot, *C*.

FIG. 2.—*A*, A full stand of large, vigorous plants, subsequently found free from root-knot and other diseases (see Pl. III, fig. 1-*A*), grown in soil receiving 3,000 c. c. of boiling water. *B*, A fair stand of slightly yellowed plants, smaller than those in *A*, later found slightly affected with nematodes and Rhizoctonia root lesions (see Pl. III, fig. 1-*B*), grown in soil treated with only 1,000 c. c. of boiling water. *C*, A very poor stand of stunted and yellowed plants, the roots of which were found badly infected with nematodes and Rhizoctonia (see Pl. III, fig. 1-*C*), grown in untreated infested soil. Note the increase in size, vigor, and number of plants resulting from the hot-water treatments. This may be due not only to reduction of root parasites, but in part also to a stimulating effect from changes of the soil, due to the heating.

TOMATO PLANTS GROWN IN 8-INCH POTS OF TREATED AND UNTREATED INFESTED SOIL OF EXPERIMENT SERIES I, TAKEN (FIG. 1) TWO WEEKS AFTER PLANTING AND (FIG. 2) AT THE END OF THE EXPERIMENT.

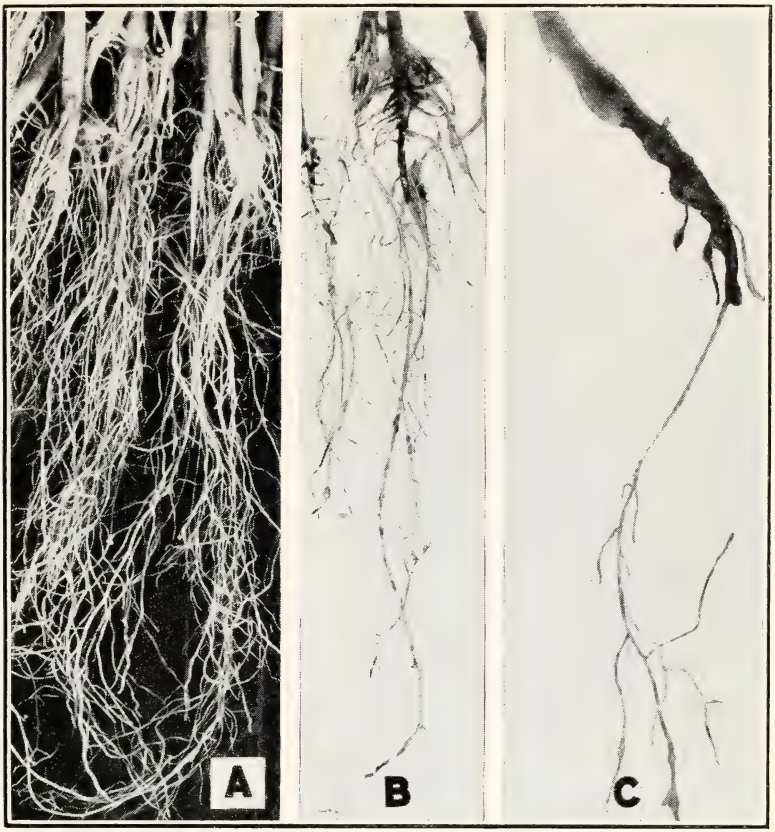

FIG. 1.—ROOTS AND STEMS OF TOMATO PLANTS TAKEN FROM 8-INCH POTS OF TREATED AND UNTREATED INFESTED SOIL, SHOWN IN PLATE II, FIGURES 1 AND 2.

A, Large disease-free root systems of plants grown in a pot treated with 3,000 c. c. of boiling water (98° C.) (natural size); *B*, smaller root systems of plants grown in a pot receiving 1,000 c. c. of boiling water (natural size). Note occasional nematode galls on lower part of roots and a small number of dark Rhizoctonia root lesions. *C*, Roots and stem of plant from check pot (enlarged 2½ times). Note large galls on stem and old part of root system and small galls on younger, newly formed root system. It should also be noted that the lower part of the taproot and practically all of the secondary roots have been destroyed by the pathogenes.

FIG. 2.—BENCH SECTIONS NO. 3 (LEFT) TREATED WITH 17,000 C. C. (3.6 GALLONS) PER CUBIC FOOT OF SOIL OF BOILING WATER (98° C.) AND NO. 4 (RIGHT) UNTREATED CHECK, EXPERIMENT SERIES I.

Note the differences as to number, size, and vigor of plants in the two sections. Pronounced differences in the root systems of the lettuce plants taken from these sections are shown in Plate IV, figure 1.

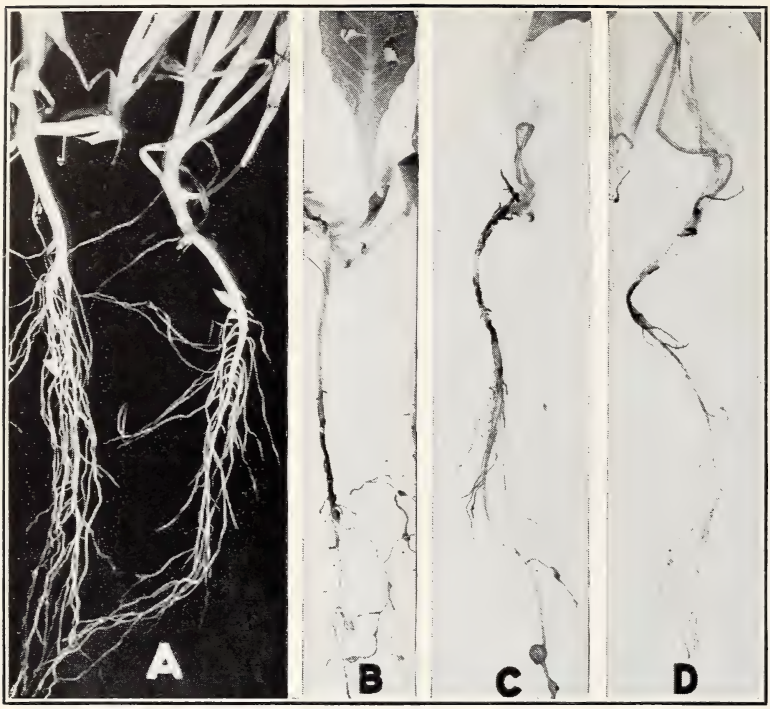

FIG. 1.—LETTUCE PLANTS FROM BENCH SECTIONS NOS. 3 AND 4, SHOWN IN PLATE III, FIGURE 2.

Note (*A*) the white, healthy, vigorous root systems from plants grown in treated section No. 3, as compared with (*B*, *C*, and *D*) the nematode infested and blackened, Rhizoctonia-diseased roots from untreated section No. 4.

FIG. 2.—TOMATO PLANTS GROWN IN 4-INCH POTS OF (A,) TREATED AND UNTREATED INFESTED SOIL AS COMPARED WITH (B,) TREATED AND UNTREATED FRESH GREENHOUSE SOIL, EXPERIMENT SERIES II.

Note the pronounced differences in size, vigor, and number of plants between the front check pot and the back treated pot. For details of results, see the text.

FIG. 1.—LETTUCE AND TOMATO PLANTS FROM 8-INCH POTS OF TREATED AND UNTREATED INFESTED SOIL FROM EXPERIMENT SERIES II.

B, Disease-free root systems of tomato plants grown in pot receiving 3,000 c. c. of boiling water (98° C.), for comparison with *A*, lettuce plants, and *C* and *D*, tomato plants, grown in check pots. Note on the check plants the abundant nematode galls on the roots and stems and the numerous black Rhizoctonia lesions.

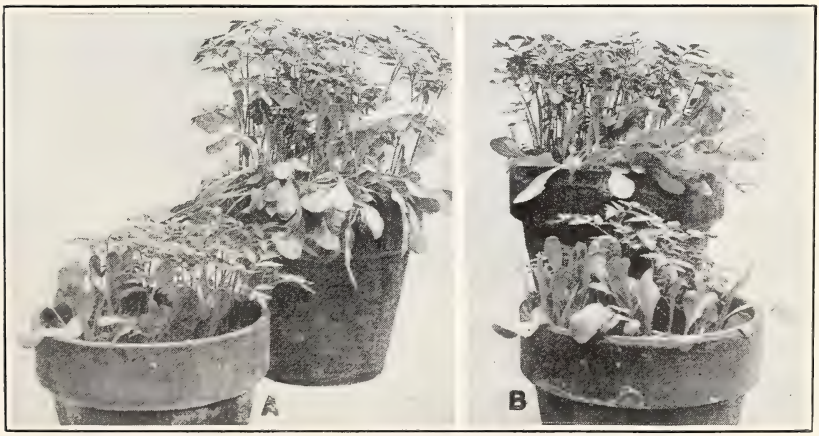

FIG. 2.—TREATED AND UNTREATED 8-INCH POTS OF (A), FRESH GREENHOUSE AND (B), INFESTED SOIL CONTAINING LETTUCE AND TOMATO PLANTS, PHOTOGRAPHED AT THE END OF EXPERIMENT SERIES II.

In the foreground note the smaller size and number of the plants in the check pots as compared with the full stand and larger size of the plants in the pots in the background treated with 3,000 c. c. of boiling water.

The object of using fresh greenhouse soil was to determine, if possible, how much of the increased growth in plants in treated soil was due to the absence of the pathogenes and how much to the chemical or physical effects of the boiling water applied.

For the bench experiment, soil from the previous bench experiment was used, with which was mixed a quantity of soil from the eelworm-infested tomato bench.

TREATMENT OF THE SOIL.

Four-inch pots.—Twelve 4-inch pots were filled with infested soil and treated as follows: Three check pots were immersed in cold water and three each immersed in boiling water at 98° C. for 2½, 5, and 10 minutes, respectively. They were allowed to dry for four days and were then sown to Stone tomatoes.

This experiment was duplicated, using greenhouse soil presumably uninfested and three additional check pots.

Eight-inch pots.—Twelve 8-inch pots were filled with infested soil and treated as follows: Three were thoroughly soaked with cold water and used as checks and three each were treated by the application of 2,000, 3,000, and 4,000 c. c. of boiling water, respectively. All were allowed to dry for four days, and were then sown to Stone tomatoes and Big Boston lettuce, one-half of each pot to each crop.

The experiment was duplicated with greenhouse soil supposedly uninfested, six checks being used instead of three.

Certain of these pots were used to determine the temperatures observed in the soil, the time required to raise the soil to the different temperatures, and the length of time the heat was maintained, the results of which are given in Table VI.

Greenhouse bench.—The bench experiment was an exact repetition of that of Experiment Series I, except as to the quantities of boiling water applied, which in this case were 11,250, 22,500, and 33,750 c. c., respectively, for sections 1, 2, and 3. These quantities were computed as approximately equivalent to 1,000, 2,000, and 3,000 c. c. per 8-inch pot of soil.

In section 3 a record of soil temperatures obtained during the treatment was kept, as in the case of the 8-inch pots. Two thermometers were inserted in the soil in different parts of the bench section to a depth of 3 to 4 inches and the temperatures recorded.

RESULTS.

The details of the results secured from this series of experiments are given in Tables III to VI in the form of germination counts, notes on disease occurrence and on the vigor and size of plants, and temperature records. The experiment was terminated on June 12, and notes on root infections were made as in Experiment Series I.

Photographs were taken to illustrate the more important results secured.

TABLE III.—*Soil-disinfection tests with tomato plants grown in 4-inch pots, with hot water treatment, in May and June, 1918.*

[Two kinds of soil were used: Soil *A* was nematode and fungus infested; *B* was uninoculated fresh greenhouse soil.]

Kind of soil and treatment of soil-filled pots.	Pot No.	Number of plants.		Results observed on June 12 (end of experiment).										
				Nematode infestation of roots.					Rhizoctonia infection of roots.		Notes on disease, size, and vigor of plants.			
		On May 18.	On June 12.	Severe.	Medium.	Mild.	Total.	Percentage.	Number of plants.	Percentage.	With stem galls.	Damped-off.	Height (inches).	Vigor.[1]
Soil *A*: Immersed in boiling water—														
2½ minutes	1	40	41	0	0	0	0	0	0	0	None....	None....	4 to 5½...	HV.
	2	37	37	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
	3	46	48	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
5 minutes.	1	47	47	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	HV.
	2	38	38	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
	3	46	46	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
10 minutes	1	48	49	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	HV.
	2	51	49	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
	3	55	55	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
Check (immersed in cold water).	1	37	33	23	4	6	33	100	30	91	Several..	Some....	1½ to 2...	SY.
	2	38	33	17	10	6	33	100	33	100	...do.....	4.....	2.....	
	3	25	15	14	0	1	15	100	15	100	0.....	5.....	1½.....	
Soil *B*: Immersed in boiling water—														
2½ minutes	1	51	49	0	0	0	0	0	0	0	None....	None....	4 to 5½...	HV.
	2	70	70	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
	3	71	67	0	0	0	0	0	0	0	...do.....	...do.....	5½.....	
5 minutes.	1	51	51	0	0	0	0	0	2	4	...do.....	...do.....	4 to 5½...	HV.
	2	55	57	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
	3	37	34	0	0	0	0	0	0	0	...do.....	...do.....	...do.....	
10 minutes	1	58	50	0	0	0	0	0	2	4	...do.....	...do.....	...do.....	HV.
	2	38	38	0	0	0	0	0	1	3	...do.....	...do.....	...do.....	
	3	50	50	0	0	0	0	0	1	2	...do.....	...do.....	...do.....	
Check (immersed in cold water).	1	47	40	0	0	6	6	15	35	87	1.....	2.....	1½.....	(2)
	2	22	23	0	0	7	7	30	3	13	0.....	0.....	2.....	
	3	36	34	0	0	8	8	23	18	70	0.....	0.....	2.....	
	4	20	21	0	0	11	11	52	16	76	0.....	0.....	1½ to 2...	
	5	23	24	0	0	12	12	50	10	41	2.....	4.....	2½.....	
	6	19	17	0	0	1	1	6	6	35	0.....	2.....	2.....	

[1] Abbreviations used: HV=Healthy and vigorous; SY=Stunted and yellow.
[2] Much smaller than in treated soil.

DISCUSSION OF RESULTS.

A close study of Table III reveals a striking confirmation of the results secured in the 4-inch pot treatments of Experiment Series I. All treatments completely eliminated nematode infection and damping-off, almost eliminated Rhizoctonia, greatly increased the percentage of germination, and markedly stimulated the growth of the

tomato plants. Again, the check plants in infested soil showed severe nematode and fungous infection and were much dwarfed and yellowed. (See Pl. IV, fig. 2.) Some of the plants grown in untreated greenhouse soil, supposedly uninfested, showed mild nematode infestation, while more than half were attacked by Rhizoctonia.

Because of the partial infestation of the greenhouse soil, it was not possible to determine how much of the increased plant growth in the soil treated with boiling water was due to the killing of the pathogenes and how much resulted from the stimulating effect of the heating.

A scrutiny of the results of the 8-inch pot treatments given in Table IV shows a verification of those secured in Experiment Series I; viz, a marked reduction of the diseases in the 2,000 c. c. treatments and their elimination in the pots which received 3,000 c. c. of boiling water (Pl. V, fig. 1), and a considerable increase in the number, size, and vigor of plants in treated pots above that shown in the check pots (Pl. V, fig. 2). As might be expected, the added 4,000 c. c. treatment gave similar results.

Again, on account of the nematodes and Rhizoctonia in the fresh greenhouse soil, no conclusive results were obtained regarding the degree of growth stimulation which might be caused by the heating alone. It may be noted that in general the percentage of germination and the plant growth were larger in the fresh greenhouse soil than in the old infested soil (Pl. V, fig. 2).

The results from the repeated bench experiment, as given in Table V, show only data from tomatoes, since the lettuce was destroyed by mice shortly after the experiment was started. Here, again, substantial confirmation of the results of Experiment Series I was secured. As in Experiment Series I, the treatment approximately equivalent to 1,000 c. c. per 8-inch pot reduced the amount of disease. In the 2,000 c. c. treatment of Experiment Series II only 11 per cent of the plants showed mild root-knot infection, as compared with 96 per cent of more severe root-knot in the check, while the 3,000 c. c. application practically eliminated the trouble.

A study of Table VI, which gives the soil temperature records, shows that in 8-inch pots treated with 3,000 and 4,000 c. c. of boiling water and in the bench section treated at the rate of 7 gallons per cubic foot of soil, all of which treatments killed the pathogenes, a relatively short time was required to raise the soil temperature to the maximum in each treatment and that the soil retained the heat for a strikingly long period. In all cases the temperature was maintained above 60° C. for more than 30 minutes and above 55° C. for 48 to 65 minutes, both temperatures being well above the thermal death point of the root-knot nematode, as determined by the first writer, and presumably above that of the fungi in question.

TABLE IV.—*Soil disinfection tests with tomato and lettuce plants grown in 8-inch pots, with hot-water treatment, in May and June, 1918.*

[Two kinds of soil were used: Soil *A* was nematode and fungus infested; *B* was uninoculated fresh greenhouse soil.]

Kind of plants, soil used, and treatment of soil-filled pots.	Pot No.	Number of plants		Root infection on June 12 (end of experiment).						Plant notes, May 28.	
				Nematode.				Rhizoctonia.			
		On May 18.	On June 12.	Severe.	Medium.	Mild.	Percentage.	Number of plants.	Percentage.	Height (inches).	Disease.
Tomato plants:											
Soil *A*—											
Boiling water poured into pots—											
2,000 c. c.	1	67	66	0	2	15	23	1	1.5	4 to 4½	None.[1]
	2	73	70	0	2	20	27	0	0	4 to 4½	
	3	64	65	0	0	35	54	3	4	4½	
3,000 c. c.	1	65	64	0	0	0	0	0	0	4 to 4½	Do.[1]
	2	70	66	0	0	0	0	0	0	4½	
	3	85	71	0	0	0	0	0	0	4½	
4,000 c. c.	1	70	55	0	0	0	0	0	0	3½	Do.[1]
	2	56	57	0	0	0	0	1	2	3½	
	3	49	45	0	0	0	0	0	0	4	
Check (soaked with cold water).	1	72	40	16	7	17	100	40	100	2 to 3	(2) (3)
	2	50	22	17	3	1	95	20	90	1½ to 2	(4) (5)
	3	57	42	26	10	4	95	40	95	2 to 2½	(2) (4)
Soil *B*—											
Boiling water poured into pots—											
2,000 c. c.	1	87	48	0	0	0	0	0	0	4½ to 5	None.[1]
	2	56	54	0	0	0	0	1	2	4	
	3	60	52	0	0	0	0	1	2	3½	
3,000 c. c.	1	60	68	0	0	0	0	0	0	5 to 5½	Do.[1]
	2	60	73	0	0	0	0	0	0	6 to 6½	
	3	63	61	0	0	0	0	0	0	4 to 4½	
4,000 c. c.	1	57	52	0	0	0	0	1	2	4½ to 5	Do.[1]
	2	48	48	0	0	0	0	0	0	5	
	3	54	51	0	0	0	0	0	0	6	
Check (soaked with cold water).	1	49	30	0	0	2	7	20	66	1½	(6) (7)
	2	32	31	0	0	18	58	27	87	4 to 5	(7) (8)
	3	40	38	0	0	5	13	16	42	3 to 4	(6) (7)
	4	45	22	14	7	1	100	22	100	4	(7) (8)
	5	43	44	0	0	22	50	15	34	4	(7) (8)
	6	42	47	0	0	17	36	4	9	2	(7) (8)
Lettuce plants:											
Soil *A*—											
Boiling water poured into pots—											
2,000 c. c.	1	77	60	0	1	13	23	0	0	3 to 3½	None.
	2	63	73	0	0	13	18	0	0	3 to 4	
	3	50	31	0	0	2	6	3	10	3	
3,000 c. c.	1	45	47	0	0	0	0	0	0	3 to 3½	Do.
	2	66	52	0	0	0	0	0	0	3 to 3½	
	3	64	52	0	0	0	0	0	0	3½	
4,000 c. c.	1	40	48	0	0	0	0	0	0	2½ to 3	Do.
	2	43	38	0	0	0	0	1	2.5	2½ to 3	
	3	37	30	0	0	0	0	0	0	3	
Check (soaked with cold water).	1	45	13	12	1	0	100	10	77	2	(9)
	2	30	22	20	1	1	100	1	4	1 to 1½	(10)
	3	43	26	21	4	0	95	12	46	2	
Soil *B*—											
Boiling water poured into pots—											
2,000 c. c.	1	71	37	0	0	0	0	1	3	3½	None.
	2	77	35	0	0	0	0	3	9	3	
	3	55	46	0	0	0	0	0	0	3	
3,000 c. c.	1	63	51	0	0	0	0	0	0	3½	Do.
	2	66	62	0	0	0	0	0	0	4 to 4½	
	3	49	47	0	0	0	0	0	0	3	
4,000 c. c.	1	40	43	0	0	0	0	0	0	3½	Do.
	2	55	34	0	0	0	0	0	0	3½ to 4	
	3	59	34	0	0	0	0	0	0	4	
Check (soaked with cold water).	1	45	44	0	0	8	18	5	11	2	Do.
	2	32	23	0	0	2	9	23	100	3	
	3	30	30	0	0	5	17	0	0	3	
	4	33	23	20	3	0	100	5	22	3½	
	5	16	13	0	0	7	54	4	31	2	
	6	47	31	0	0	7	22	0	0	1½	

[1] Plants vigorous.
[2] Damped-off, few.
[3] Nematode stem galls, many.
[4] Damped-off, many.
[5] Nematode stem galls, few.
[6] Damped-off, 1.
[7] Nematode stem galls, none.
[8] Damped-off, none.
[9] Several plants damped-off and some with stem galls.
[10] No damping-off, but several plants with stem galls.

TABLE V.—*Soil-disinfection tests with tomato plants grown in shallow bench sections, with hot-water treatment, in May and June, 1918.*

[The bench sections were filled with nematode and fungus infested soil thoroughly mixed by sifting.]

Bench section. No.	Application of boiling water (at 98° C.).			Total plants.	Root infection on June 13 (end of experiment).							Plant notes, May 28.	
					Nematode.					Rhizoctonia.			
	Total quantity.	Number of doses.	At rate per 8-inch pot.		Severe.	Medium.	Mild.	Total.	Percentage.	Number of plants.	Percentage.	Height.	Vigor.
	C. c.		*C. c.*									*In.*	
1	11,250	1	937	107	0	8	70	78	73	0	0	5	Healthy.
2	22,500	1	1,875	66	0	0	7	7	11	2	3	4	Do.
3	33,750	2	2,812	126	0	0	3	3	2	2	2	4–5	Do.
4 check[1]				102	2	38	58	98	96	2	2	4	(2)

[1] Saturated with cold water.

[2] One plant damped off.

TABLE VI.—*Record of temperatures in hot-water disinfection tests of soil in 8-inch pots and bench sections.*

[Treatments were with boiling water (at 98° C.). Two series of time observations (in minutes) were made, as follows: Series *A*, time required to reach the temperature indicated; series *B*, time during which soil temperatures remained above the points indicated. Temperatures were ascertained by inserting standard thermometers to a depth of 3 to 4 inches in the center of the pots and at two points in the bench section (No. 3).]

Observation data.	Water applied (c. c.).	Pot No.	Thermometer No.	Temperatures (° C.).														
				50	55	60	64	66	70	72	75	76	77	78	79	80	81	82	83
Time, series *A*:		1		....	4	....	....	6	....	7	9	10	....	....	....	....	....	....	....
	3,000	2		....	5	....	....	6	....	7	7.5	....	....	8.5	9	10	10.5	....	....
8-inch pots		3		....	4	....	....	5	....	6	6.5	....	....	7	....	8	9	....	....
	4,000	1		....	2.5	....	....	4	....	4.5	5	....	....	6	....	6.5	7	7.5	9
		2		....	5.5	....	....	6.5	....	7.5	8	....	....	9	9.5	10	12.5	....	....
Bench section[1]	33,750		1	3	....	4	....	....	5	....	6	....	7	....	....	....	....	....	....
			2	7.5	8.5	9.5	13	....	....	....	....	....	....	....	....	....	....	....	....
Time, series *B*:		1		....	....	....	....	33	....	19	9	5	....	....	....	....	....	....	....
	3,000	2		....	....	....	....	28	....	19	....	13	....	9.5	....	4	....	....	....
8-inch pots		3		....	57	....	....	33	....	23	16.5	....	....	11	....	7	....	....	....
	4,000	1		....	65.5	....	....	40	....	27.5	22	....	....	14	....	10.5	9	6.5	....
		2		....	63.5	....	....	38.5	....	25.5	20	....	....	14	....	8	3.5	....	....
Bench section[1]	33,750		1	10.2	61.5	53	41.5	....	....	....	10	....	....	....	....	....	....	....	....
			2	80.5	48.5	36.5	....	....	....	....	....	....	....	....	....	....	....	....	....

[1] The application of hot water to the bench section (No. 3) was at the rate of 3,000 c. c. per 8-inch pot of soil.

SUMMARY.

1. The root-knot nematode (*Heterodera radicicola*), Rhizoctonia species, and *Pythium debaryanum* can be eliminated from soil in 4-inch pots by submersion for 5 minutes in water at 98° C. (208° F.).

2. These organisms can also be killed in 8-inch pots by the application of 3,000 c. c. of water heated to 98° C. (208° F.). This treatment is the equivalent of an application of about 7 gallons per cubic foot of soil.

3. These pathogenes are almost entirely destroyed in 8-inch pots by treatment with 2,000 c. c. of boiling water (5 gallons per cubic foot).

4. In shallow benches an application of boiling water at the rate of 7 gallons per cubic foot of soil resulted in the practical elimination of the parasites.

5. For use in treating seed boxes this method will find an immediate and practical application, particularly in connection with the boys' and girls' garden-club work. The size of the box or flat commonly used is 14 by 30 by 3 inches, and to treat this 4½ gallons of boiling water is necessary.

6. As a further result of these treatments there was in all cases a marked increase in the percentage of germination and in the size and vigor of the plants grown in the treated soil as compared with the checks.

7. The treatments which were effective in killing the pathogenes maintained the temperature of the soil above 55° C. for 30 to 60 minutes, as indicated by a thermometer inserted 3 to 4 inches below the surface of the soil.

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